REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)

2. REPORT DATE
25 November 2001

3. REPORT TYPE AND DATES COVERED
01 Sep 98 - 31 Aug 01
Final Report: 1/9/98-31/8/01

4. TITLE AND SUBTITLE
Single Electron Phenomena in Semiconductor Structures

5. FUNDING NUMBERS
DAAG 55 - 98 - 1 - 0457

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8. PERFORMING ORGANIZATION REPORT NUMBER
RG 26657 - FINAL

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
38960.1-PH

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT
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12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)
This report contains a summary of the work carried out on the quantised dc current produced by the transmission of Surface Acoustic Waves through a narrow channel in a GaAs-AIGaAs heterostructure. It is shown that dynamic modulation of the potential at the channel entrance produces a significant effect on the quantisation: The technology of deviced fabrication was investigated, etched in-plane gates utilising the 2D electron gas produced a harder confinement than metal split gates. Single electron transport through dots fabricated with two-level metallisation was studied and it is concluded that this is a very promising technique for high frequency operation.

14. SUBJECT TERMS

15. NUMBER OF PAGES
4

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

20020131 135

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Professor M Pepper

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TITLE:	SINGLE ELECTRON PHENOMENA IN SEMICONDUCTOR STRUCTURES
TYPE OF REPORT:	FINAL PROGRESS REPORT
AUTHOR:	M PEPPER
DATE:	25 NOVEMBER 2001
TO:	U.S. ARMY RESEARCH OFFICE
CONTRACT NO:	DAAG 55 - 98 - 1 - 0457
INSTITUTION:	UNIVERSITY OF CAMBRIDGE

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Problem Studied

The use of single electrons represents one of the most important results of all the work on semiconductor nanostructures and the manipulation of the single electrons at high frequencies has many possible applications. However conventional techniques using quantum dots driven by high frequency signals applied to entrance and exit regions do not result in accurate quantised transport, the probability of transferring one electron per cycle decreases with increasing frequency. In this work we have utilised a new technique the application of Surface Acoustic Waves to propel electrons through the chip by trapping them in the potential minimum of the wave. By passing the trapped electrons through a narrow channel defined by split gates it is possible to reduce the number of electrons to one per cycle and in this way observe a quantised current at Gigahertz frequencies.

Summary of Results

The manipulation of single electrons on a semiconductor chip can in principle lead to advances in a range of applications such as sensors, single electron logic and memories, current standard and high accuracy measurement of the fundamental charge, quantum communications and computation. In general the basic operation of single electron devices is by means of electron tunneling into a dot or enclosed region. The capacitive charging energy is e^2/C and this restricts electron transport through the dot to one at a time, the so-called Coulomb Blockade, the result is a series of current peaks as a function of gate voltage. In order for the single electron transport to be exactly defined there has to be a tunneling barrier and a resistance which exceeds $h/2e^2$. Otherwise the individual levels in the dot, separated by the charging energy, would be smeared by lifetime broadening, and the discrete nature of the states would not be observed. This has given rise to the use of high frequency voltages applied to the dot entrance and exit regions which will transport a single electron at each stage of the cycle. This gives a dc current I, where I=nef, n is the number of electrons transported during the cycle in this case one, f is the frequency and e is the electron charge. However there is a fundamental problem in that because the tunneling is essential and as this is an inherently statistical process so, at high frequencies, slippage can occur and the current is less than that predicted. In order to obtain a current which does not deviate from the predicted value by more than 1.0 % it is necessary to restrict the frequency to the Megahertz region with a consequent current in the picoAmp range. This level of current is too small for many applications.

The purpose of this program of research was to investigate the application of high frequency manipulation of single electrons by transmitting Surface Acoustic Waves (SAW's) across a GaAs chip, the quantised acousto-electric effect. The waves constitute a travelling wave modulation of the conduction band and electrons are trapped in the potential minima and transported across the chip by the waves. The number of electrons in each minimum can be as great as 20 depending on the amplitude of the signal but by passing the wave through a narrow channel defined by split or patterned gates it is possible to reduce the number down to one and then zero. As the gate voltage is made more negative a series of current steps appear having values I= nef, until the gate voltage changes sufficiently that n changes by one and the next step is observed. We have

established that, as implied by the underlying physics, the flatter the current step then the more accurate is the value of the mid-point. As highly accurate measurements are very slow, and demanding on experimental precautions, this result was valuable in that it meant the flatness of the plateau could be measured as an excellent guide to the absolute accuracy.

The papers published under the auspices of the grant are listed below. Paper 1) describes the attempt to influence the accuracy of electron transport by SAW's of frequency 2.68 Gigahertz. The motivation was that the flatness of the quantised current step is typically about 0.01% and part of this can be attributed to the reflection of electrons from the surface potential wells as they experience the potential change at the entrance to the channel. If a SAW of considerable less amplitude (about 10%) is sent in the reverse direction then the potential at the channel entrance is altered by modification of the phase of the counter-propagating wave. The incident wave and the, weaker, counter-propagating wave can be considered to comprise a standing wave and travelling wave and it is this standing wave which modifies the potential at the entrance. It was found that in this way it was possible to alter considerably the shape of the current step and produce a flatness of plateaux of better than 0.005% considerably better than in the absence of the counter-propagating wave. However by varying the phase it was also possible to completely remove the plateau as well as improving it, a very surprising effect.

The previous measurements used metal split gates to define the confining channel potential. It was thought that there were two possible improvements to this approach, first the metal could screen the SAW's and reduce the amplitude of the potential minima. Any attempt to compensate for this by increasing the power would run into difficulties because of the possibility of sample, and electron gas, heating. The second possible improvement was that the confining potential induced by the metal gates was too shallow to obtain significant separation of the energy levels in each potential minimum. In order to improve on this a technique developed at the University of Copenhagen was utilised, references 2) and 3). Here the electron gas is etched away from a narrow region, to define an insulating region, and the outside electron gas is then used as an in-plane gate to narrow the electron gas left between the etched regions. This technique has been known to produce very strong confinement in one-dimension with pronounced plateaux of quantised conductance. We found that the plateaux of quantised current could be flatter than using metal split gates and were very similar to the flattest with the counter-propagating SAW. It was also found that the change in the plateau value with bias along the channel was substantially reduced owing to the increased separation of the energy levels.

The role of a magnetic field was investigated, and it was found that when this exceeded the value for establishment of edge states the plateaux were removed. However at lower fields there was an increase in the length of the plateau, and often the flatness, and a weak oscillatory behaviour in the flatness which was attributed to commensurability effects. This appears due to the reduction in the probability of back tunnelling as electrons are pushed to the sides of the channel due to the incipient formation of cyclotron orbits. The effects of the magnetic field require further study.

In a parallel series of experiments the shot noise was investigated 4). The motivation was that such noise would arise from fluctuations in the well occupancy, thus the first plateau corresponding to one electron in each well would be " noisy" due to a certain probability of occupancy of 0 and 1. The noise was measured at 2 kHz where the current off the plateau was affected by the Random Telegraph Signals frequently a problem in the mesoscopic regime. However on the plateau this source of noise was suppressed. The shot noise was found to be immeasurably small and was much less that predicted by Poisson statistics indicating that the regularity of the transfer of individual electrons was invalidating the normal theory of current noise. It was not possible to investigate the extremely low level of noise predicted by a simple model we derived and future work will concentrate on higher frequencies where the shot noise is enhanced.

The theory of the device as applied to quantum computation has been considered, in an ongoing exercise, as the interaction of two SAW beams ~~may~~ give rise to useful properties. Two electrons in SAW potential well will be in an entangled state and, if a viable read-out mechanism were obtained, then this could be used as well.

In a series of parallel experiments different sample configurations were investigated in order to determine if improvements could be made to simple split gates, 5), 6). The sample design comprised a double layer of metallisation, a lower split gate structure was fabricated in which the separation of the two gates was about 0.7 microns and the channel length was similar. A layer of resist was deposited over the split gates and then two metal bars were fabricated across the channel, these were 0.15 microns in width and were separated by a similar amount. This modification was characterised and found to work as a one-dimensional channel with controllable reflections and resonances when the negative voltage applied to the bars was low. Increasing the magnitude of the negative gate voltage formed a quantum box showing Coulomb Blockade. When the voltage was positive then one could have two or three one-dimensional channels in series. This device has very useful properties and, in future, transducers will be fabricated and the acousto-electric current studied as a function of the device parameters. To summarise, it was shown that the quantised acousto-electric effect can be manipulated by the establishment of a counter-propagating Surface Acoustic Wave. This adds considerable flexibility to its potential as a supply of an extremely accurate number of electrons. It was shown that the etching of in-plane gates, formed from the electron gas itself, can be used in device design, with improved quantisation. This has considerable advantages for fabricating arrays and/or sequences of devices in which the etching can be combined with metallisation to produce integrated quantum structures. An additional device was studied in which two-level metallisation provided greater control over the dimensionality going from one to zero with promise for acousto-electric single electron effects.

Refereed Papers Published

1. J. Cunningham, V. I. Talyanskii, J. M. Shilton, M. Pepper, M. Y. Simmons and D. A. Ritchie, Single-electron acoustic charge transport by two counterpropagating surface acoustic wave beams, Phys Rev B, 60, 4850, 1999

2 .J. Cunningham, V. I. Talyanskii, J. M. Shilton, M. Pepper, A. Kristensen and P. E. Lindelof , Single-electron acoustic charge transport on shallow-etched channels in a perpendicular magnetic field, Phys Rev B, 62, 1564, 2000.

3. J. Cunningham, V. I. Talyanskii, J. M. Shilton, M. Pepper, A. Kristensen and P. E. Lindelof, Quantized acoustoelectric current - an alternative route towards a standard of electric current, JLTP, 118, 5, 555, 2000

4. A. Robinson, V. I. Talyanskii, M. Pepper, J. Cunningham, E. H. Linfield, Measurements of noise caused by switching of impurity states and of suppression of shot noise in surface-acoustic-wave-based single electron pumps, Phys Rev B, at press, 2001

5. Evidence for charging effects in an open dot at zero magnetic field, C.-T. Liang, M.Y. Simmons, C.G. Smith, G.H. Kim, D.A. Ritchie and M. Pepper, Physica E 6, 418-422 (2000).

6. Multilayered gated lateral quantum dot devices, C.-T. Liang, M.Y. Simmons, C.G. Smith, G.H. Kim, D.A. Ritchie and M. Pepper, Appl. Phys. Lett. 76, 1132-1134 (2000).

Conference Talks

M Pepper presented an invited plenary talk at the 2000 conference on Precision Electromagnetic Measurements, Sydney, Ausrtralia.

Participating Scientific Personnel

Professor M Pepper , Dr V Talyanski and Dr J Cunningham (partly supported), Mr A Robinson (graduate student) on experimental aspects. Dr Cunningham received his Ph.D in 2000 for his work on the project.

Dr C Barnes provided theoretical advice and expertise.